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THE LOGARITHMIC DEPENDENCE OF SURFACE-GENERATED AMBIENT SEA NOI--ETC(U)
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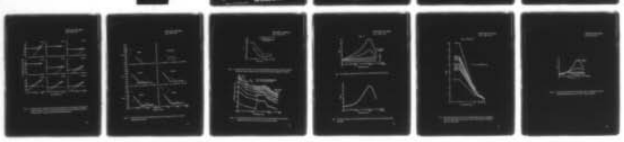

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THE LOGARITHMIC DEPENDENCE OF SURFACE-GENERATED AMBIENT SEA NOISE SPECTRUM LEVEL ON WIND SPEED

by

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ABSTRACT

A mathematical description of ambient sea noise is presented that takes into account the two dominant sources — surface agitation and distant shipping. The contribution from surface agitation is shown to be linearly dependent upon the logarithm of wind speed for depths between 400 and 2500 fm at several sites near Bermuda. When this is taken into account, the ambient-noise data that include both sources can be analyzed to determine the individual levels of the sources. Also, the standard deviations of the two sources can be determined from the standard deviations of the measured levels.

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INTRODUCTION AND SUMMARY

Although many sources of ambient sea noise have been identified, in most areas two sources dominate between 10 and 10,000 Hz. One source is non-wind-dependent and believed to be primarily distant shipping. The other source is wind-dependent and believed to be surface agitation near the measuring device. This is borne out in a survey of many ocean areas by Wenz[1] and in measurements made near Bermuda by Perrone.[2,3]

Piggott, using data taken in very shallow water, found that the noise spectrum level attributed to the wind-dependent source was proportional to the logarithm of wind speed.[4] His study was conducted on the Scotian Shelf in 20 and 28 fm of water. However, because of the greater complexity of deep-water data, his findings have not been previously substantiated for other locations and other depths. We have found that independently obtained sets of data taken at several sites near Bermuda in depths up to 2500 fm also demonstrate the logarithmic relationship.

The conclusions that only two sources are important and that the contribution from the wind-dependent source is linearly related to the logarithm of wind speed simplify ambient-noise prediction and analysis. The former conclusion has been taken into account for some time, but it still has been difficult to separate the relative contributions of the two sources in measured levels. And it has been equally difficult to estimate the standard deviations of the two contributions from the standard deviations of the measured levels. However, the linear dependence that Piggott[4] discovered, and which is substantiated here, makes it possible to express mathematically the noise levels and standard deviations as functions of wind speed for a given frequency. The spectrum levels and the standard deviations of the contributions from both sources can be obtained by finding the mathematical equation of the appropriate form that best fits the data.

Section I provides the necessary mathematical expressions. Section II demonstrates that the linear relationship does exist in several sets of deep-water data. And Section III discusses applications of the mathematical relationships in determining the spectrum levels and the standard deviations of the contributions from the two sources.

I. THEORY

Piggott studied the wind dependence of ambient sea noise at two depths in very shallow water (20 and 28 fm) where the contribution from the wind-dependent source was dominant at nearly all wind speeds and all frequencies.[4] He found that at wind speeds where the contribution from the wind-dependent source was dominant, the spectrum level (in decibels) was linearly dependent on the logarithm of wind speed (Eq. 2, below). His data also suggest that the measured levels at all wind speeds and at all frequencies could be described as the sum of the contributions from two sources — the wind-dependent source and the non-wind-dependent source.

Mathematically, measured levels can be represented as the sum of two portions (The notation is chosen to be consistent with Piggott's notation.[4]):

$$L_1(f) = A(f) \tag{1}$$

$$L_2(f, v) = B(f) + 20\, n(f) \log v, \tag{2}$$

where

$L_1(f)$ spectrum level in decibels of the non-wind-dependent portion

$L_2(f, v)$ spectrum level in decibels of the wind-dependent portion (as published by Piggott)

$A(f)$ spectrum level in decibels of the non-wind-dependent portion

$B(f)$ spectrum level in decibels of the wind-dependent portion at 1 knot wind speed

$20n(f)$ slope of the wind-dependent portion in decibels per decade

v wind speed in knots

The level resulting from random phase summation of L_1 and L_2 is

$$L(f, v) = 10 \log \left(10^{L_1/10} + 10^{L_2/10} \right) . \qquad (3)$$

II. ANALYSIS

In Piggott's study,[4] the wind-dependent portion was dominant at wind speeds above 25 knots for frequencies from 8 to 140 Hz; at higher frequencies (up to 3000 Hz), the wind-dependent portion was dominant at all wind speeds. He was able to fit straight lines to the wind-dependent portions by eye and thus confirm that the linear relationship existed. One would expect the linear relationship he found to hold at other locations, but it would not be so pronounced if the non-wind-dependent portion was relatively higher.

Data have been taken by New London Laboratory scientists with several arrays near Bermuda that show ambient-noise levels as a function of wind speed. Perrone[2,3] provided the most extensive data, and data also were available from two other studies.[5,6] The hydrophones were at depths between 400 and 2500 fm.

In all cases, when these data were plotted as spectrum levels in decibels vs logarithm of wind speed, it appeared that the wind-dependent portion might exhibit a linear dependence at higher wind speeds for some frequencies. It was not possible, however, to choose the appropriate straight line by eye as Piggott[4] had done. At many frequencies, the wind dependence consisted only of a small rise in level at the highest wind speeds.

In order to find the parameters B(f) and n(f) of the linear relationship for these data, we used the mathematical relationship of Eq. 3. The appropriate B(f) and n(f) can be determined by finding a best-fit curve of that form. The advantage of this method is that it uses all data points even though many of them represent the predominantly non-wind-dependent portion. The non-wind-dependent portion $L_1(f)$ also is calculated in the analysis. We defined the best-fit curve as that curve for which the sum of the squares of the vertical distances between the data points and the curve was minimized.

At all frequencies where there was evidence of a wind-dependent portion (generally at 10 to 15 Hz, 25 to 40 Hz, and above 100 Hz), such a curve could be fitted to all the sets of data. Perrone's data[2] are used here to demonstrate the results. The data and the best-fit curves are shown in Fig. 1. Each curve is defined by the three parameters A(f), B(f), and n(f), and a different set applies to each frequency (see Table I).

Surprisingly little wind dependence was needed for a best-fit curve to be calculated showing the character of the wind dependence. Only when there was no increase in the spectrum levels, even at the highest wind speeds, was it impossible to get a fit. However, when there was minimal wind dependence, B(f) and n(f) were not reliable. From Perrone's data,[2] reliable B(f)'s and n(f)'s were obtained for 11 Hz, 28 Hz, and for all frequencies above 112 Hz. At 14, 28, and 89 Hz, unreliable B(f)'s and n(f)'s were obtained; at the other frequencies, the non-wind-dependent portion was dominant even at a 50-knot wind speed. Similar results were obtained with the other sets of data.

The data generally fall at small random distances from the best-fit curves; however, two small, but systematic, variations can be noted. One could be described as a "waviness" of the data. At the higher wind speeds, the data for many frequencies meander about the best-fit curve in the same manner. This is evident at 1414 and 2816 Hz in Fig. 1. The variation is only 1 or 2 dB and may be the result of data-sorting and editing techniques. However, a physical explanation can not be ruled out.

Also, there is some indication that the data may flatten out at the higher wind speeds. This characteristic can be seen in the data for 707 Hz in Fig. 1. Piggott's results[4] do not provide any information for wind speeds above 35 knots. The apparent flattening appears above that wind speed. A possible explanation of the flattening is that a maximum level of the wind-dependent portion is reached, but the effect is not pronounced enough to warrant any conclusions at this time.

Figure 2 shows n(f) as a function of frequency for all the data analyzed. The sets of data are labeled by depth: 400, 1100, and 2500 fm are from an article by Perrone,[3] 700 to 1100 fm and 2100 fm are from unpublished reports,[5,6] and 2400 fm is from the set of data by Perrone[2] that is used in this article to demonstrate the results. A function represented by two line segments seems to be suggested by the data for the four greatest depths. The line segments correspond to two of the three derived by Piggott,[4] but they are lower (see Fig. 3). Also shown are n(f)'s found by Payne[7] in 20 fm of water.

From the six sets of data analyzed in this study and the two sets of data previously published,[4,6] one can see that n consistently falls into an orderly pattern as a function of frequency. In most cases, the pattern is similar to that originally determined by Piggott[4] in 20 and 28 fm of water. However, the pattern is found to be lower in Payne's data[7] for 20 fm of water and in four sets of New London Laboratory data (1100 through 2500 fm). Also, two sets of New London Laboratory data (400 and 700 through 1100 fm) do not conform well to the shape of the pattern. There is no obvious depth effect, nor is it otherwise clear why the differences exist. The relatively large values of n(f) around 891 Hz, which appear in several sets of data, are also curious and not yet explained.

III. APPLICATIONS

A. Spectrum Levels of the Two Sources

When measured ambient-noise levels are represented by Eq. 3, $L_1(f)$ and $L_2(f, v)$ are estimates of the two component portions. In Section II, we showed that Perrone's data[2] could be so represented, and we calculated the parameters A(f), B(f), and n(f), which are necessary for specifying $L_1(f)$ and $L_2(f, v)$, and, thus, $L(f, v)$ for each frequency.

Figure 4 shows the calculated levels of the non-wind-dependent portion, $L_1(f)$, and the wind-dependent portion, $L_2(f, v)$. The latter portion, given by Eq. 2 using B(f) and n(f) from Table 1, is plotted for wind speeds of 1, 5, 10, 20, 30, 40, and 50 knots. Although B(f)'s and n(f)'s were found for 14, 28, and 89 Hz, they were judged unreliable and are not used here. Calculations were made for 11 and 35 Hz and 112 through 1414 Hz, and $L_2(f, v)$ was estimated by extrapolation at the other frequencies. The non-wind-dependent portion is given by Eq. 1 using A(f) from Table I. One can readily see that when the wind- and non-wind-dependent portions are combined they give the measured levels.

The process of "least-square" fitting a curve of the shape given by Eq. 3 is mathematically complex. Therefore, simplified techniques were considered. In extreme cases when all data at a given frequency are wind-dependent, as in shallow-water data (Piggott[4]), or non-wind-dependent, as it is at several frequencies in deep water, a suitable estimate of the dominant source may be obtained "by eye" or by simple straight-line fitting techniques. In other cases, where contributions of both sources are significant, the noise level for wind speeds below about 5 knots will generally be predominantly non-wind-dependent, and may be taken as a rough estimate of L_1 in Eq. 3. This suggests that a rough estimate of L_2 can be obtained by (1) subtracting L_1 from each data point and then (2) performing a simple straight-line fit. Unfortunately, such an analysis is unsatisfactory. Considerably less data are used in the estimate of L_1, which means greater probable error, and errors in L_1 are amplified at low wind speeds when it is subtracted from the data. The resultant error in L_2 proves unacceptable.

B. Standard Deviations of the Two Sources

When Eq. 3 applies, the variation of measured levels about their mean would result from the combined variations of the two portions. A mathematical model for the combination is given below in terms of the standard deviations of two Gaussian distributions.

The standard deviation of the measured levels is given by

$$\sigma = \sqrt{\left(\sigma_1(f)\frac{dL}{dL_1}\right)^2 + \left(\sigma_2(v)\frac{dL}{dL_2}\right)^2} \quad , \qquad (4)$$

where

$\sigma_1(f) \equiv$ standard deviation of the non-wind-dependent portion,

$\sigma_2(v) \equiv$ standard deviation of the wind-dependent portion,

$$\frac{dL}{dL_1} = \frac{10^{\frac{L_1}{10}}}{10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}}} ,$$

and

$$\frac{dL}{dL_2} = \frac{10^{\frac{L_2}{10}}}{10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}}} .$$

L_1, L_2, and L are given by Eqs. 1, 2, and 3. This is only an approximate relationship but adequate for the data currently available.

Figures 5 and 6 are the results of applying the above model to the standard deviations associated with Perrone's data[2] for all frequencies and for wind speeds of 5, 20, 30, 40, and 50 knots. Figure 5a shows the measured standard deviations.

Since it is not possible to solve explicitly for sets of σ_1 and σ_2, we first estimated σ_1 then calculated σ_2. We did this for frequencies at and above 224 Hz because the model can not agree with the data at frequencies where the measured levels were totally non-wind dependent. The data show a wind dependence in the standard deviation of those frequencies, but the model shows $\sigma = \sigma_1(f)$. Figure 5b illustrates the estimate of σ_1 (for 224 Hz and above) that gave the most consistent results for σ_2. The σ_1's below 224 Hz were chosen as equal to the measured values of σ for 5-knot wind speed. The σ_2's calculated are shown in Fig. 5c. Perrone concluded that σ_2 was probably independent of frequency[2]; we found no consistent dependence. Thus, the dashed line in Fig. 5c is taken as the best estimate of σ_2.

The validity of the analysis is checked by combining the σ_1's from Fig. 5b and the σ_2's from Fig. 5c. Figure 6 shows the σ's thus calculated. They are a good approximation of the measured values. The only major difference is the non-wind-dependence of σ at frequencies where spectrum levels were also found to be non-wind-dependent.

This method of determining σ_1 and σ_2 is not exact, and one is tempted to shift σ_1 and σ_2 slightly to get a better fit. We did not find this to be useful because of the limited data available to us. Researchers with data that have not been smoothed and that cover a wider frequency range may have more success in determining reliable estimates of σ_1 and σ_2. The primary purpose of this discussion is to demonstrate the usefulness of the technique. The results should be taken only as a tentative estimate of what σ_1 and σ_2 may be.

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Table I

PARAMETERS OF THE BEST-FIT CURVES

Frequency (Hz)	A(f)	B(f)	n(f)
11	-11.31	-64.35	1.73
14	-15.05	-81.23	2.07
17	- 7.01		
22	- 8.42		
28	-16.48	-88.53	2.09
35	-18.59	-69.87	1.38
44	-17.73		
56	-14.03		
70	-17.49		
89	-27.69	-125.86	2.77
112	-28.03	-73.17	1.30
141	-30.58	-74.80	1.39
177	-34.20	-55.54	.81
224	-37.14	-59.01	.93
281	-38.87	-57.64	.87
354	-38.61	-58.11	.93
446	-41.36	-56.93	.90
562	-44.27	-58.72	.92
707	-49.49	-65.66	1.09
891	-50.77	-69.82	1.15
1122	-52.51	-69.25	1.03
1414	-55.82	-69.43	.97
1778	-54.54	-71.15	.96
2241	-52.99	-71.41	.93
2816	-54.79	-73.95	.96

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2. A. J. Perrone, "Deep-Ocean Ambient-Noise Spectra in the Northwest Atlantic," J. Acoust. Soc. Amer. 46, 762-770 (1969). (Navy Underwater Sound Lab.* Rept. No. 935, The Correlation of Deep-Open-Ocean Ambient-Noise Spectra with Wind Speed and Wave Height for Frequencies from 11 to 2816 Hz, 4 Sept. 1969, also by A. J. Perrone, is an analysis of the same data. Additional plots of spectrum level vs wind speed are provided.)

3. A. J. Perrone, "Ambient-Noise-Spectrum Levels as a Function of Water Depth," J. Acoust. Soc. Amer. 48, 362-370 (1970). (Navy Underwater Sound Lab. Rept. No. 1049, Ambient Noise Spectrum Levels as a Function of Water Depth, 19 Nov. 1969, also by A. J. Perrone, is an analysis of the same data. Additional plots of spectrum level vs wind speed are given.)

4. C. L. Piggott, "Ambient Sea Noise at Low Frequencies in Shallow Water of the Scotian Shelf," J. Acoust. Soc. Amer. 36, 2152-2163 (1964).

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6. W. A. Von Winkle, M. L. Freeman, J. H. Rogers, and G. L. Assard. Unpublished Navy Underwater Sound Laboratory report, 3 Feb. 1964.

7. F. A. Payne, "Further Measurements on the Effect of Ice Cover on Shallow Water Ambient Sea Noise (L)," J. Acoust. Soc. Amer. 41, 1374-1376 (1967).

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*On 1 July 1970, the Navy Underwater Sound Laboratory became the New London Laboratory of the Naval Underwater Systems Center.

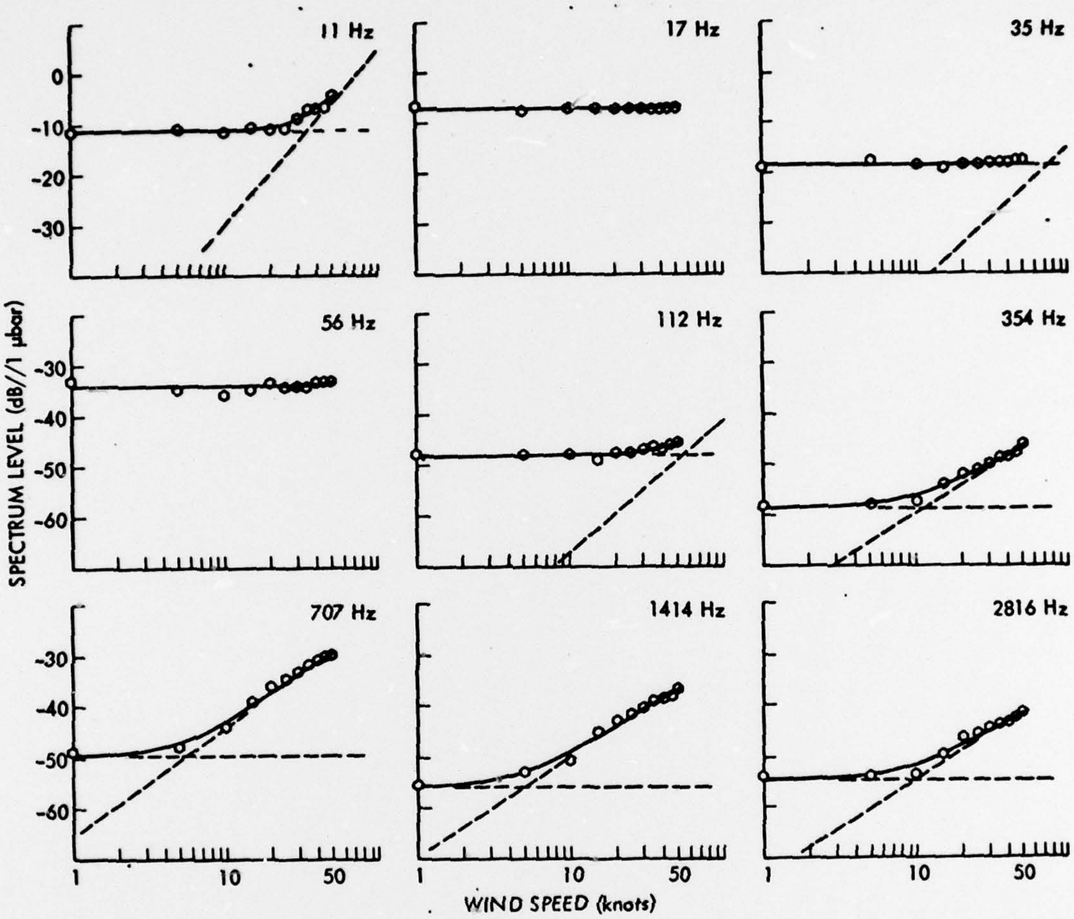


Fig. 1. Ambient noise spectrum levels vs the logarithm of wind speed showing the best-fit curves. The non-wind-dependent and wind-dependent portions of the best-fit curves are shown by the dashed lines.

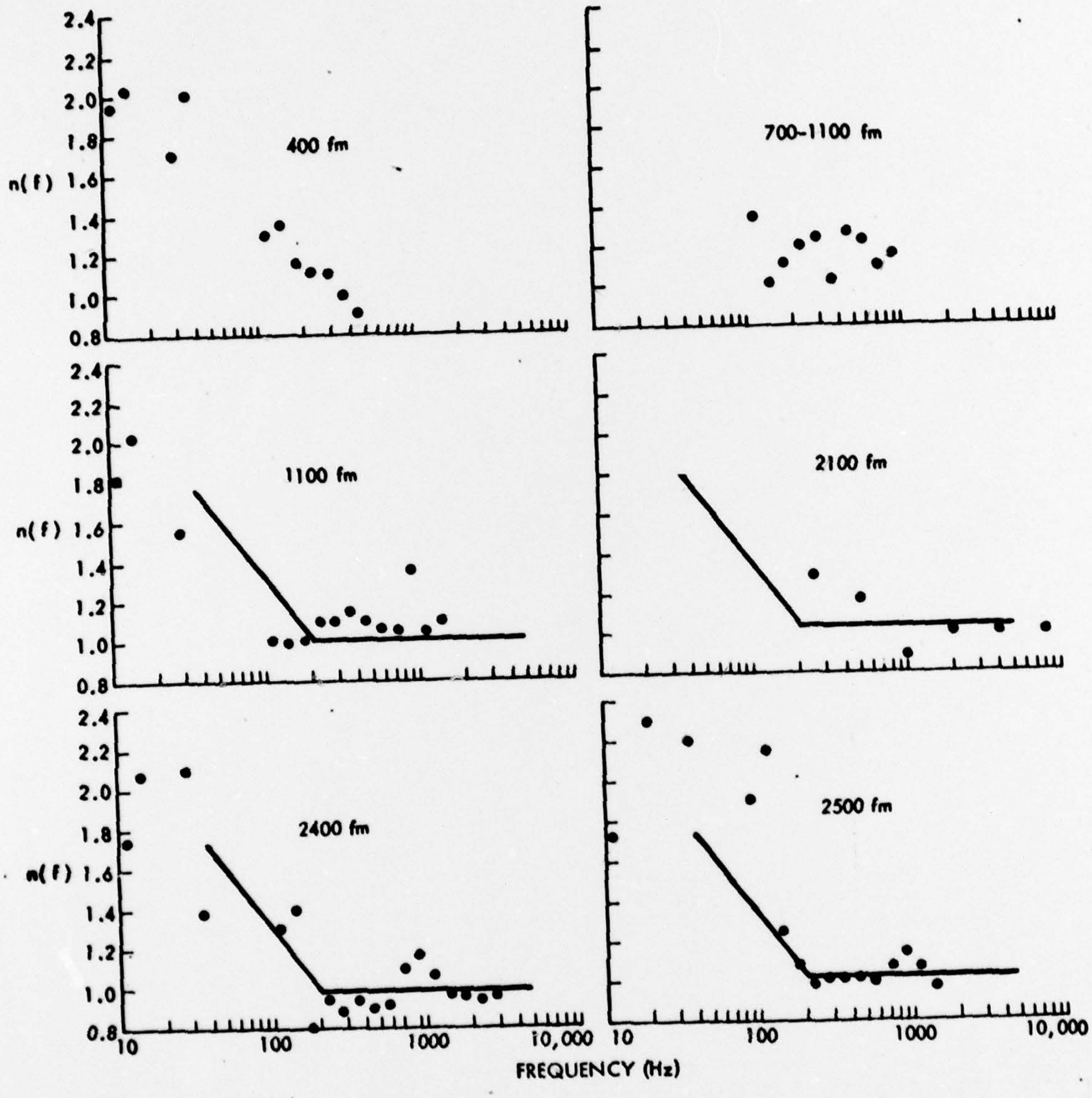


Fig. 2. The slope of the wind-dependent portions vs frequency for six sets of ambient-noise data.

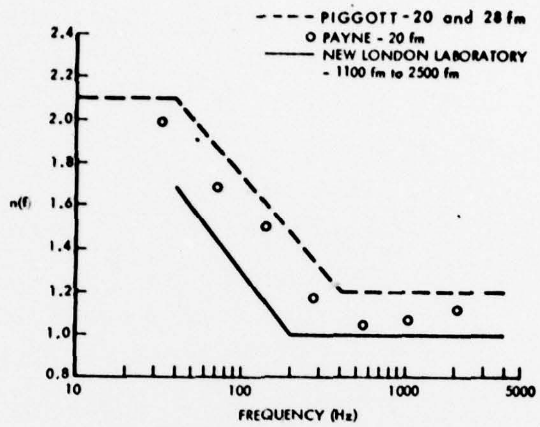


Fig. 3. Representative slopes of the wind-dependent portion for the New London Laboratory data compared with the slopes found by Piggott and Payne.

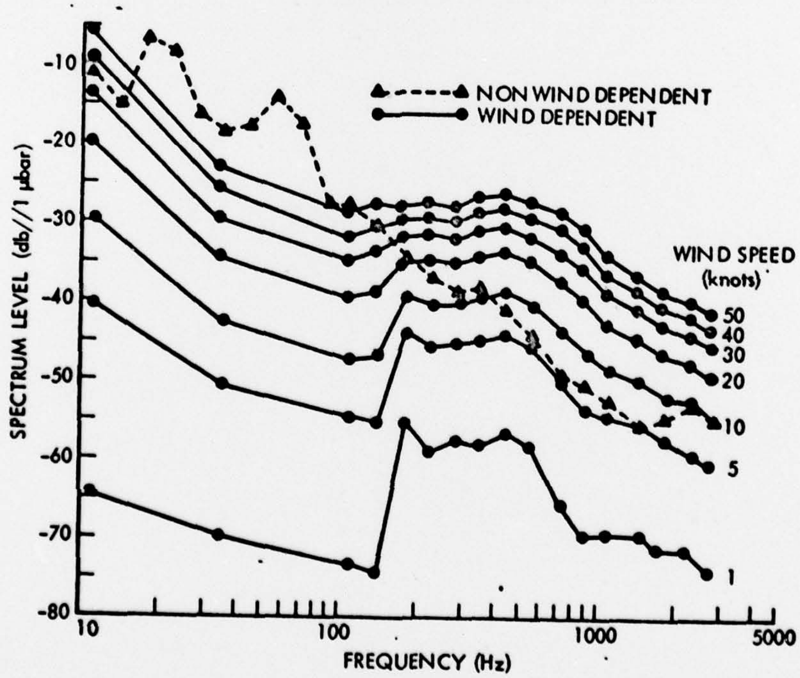
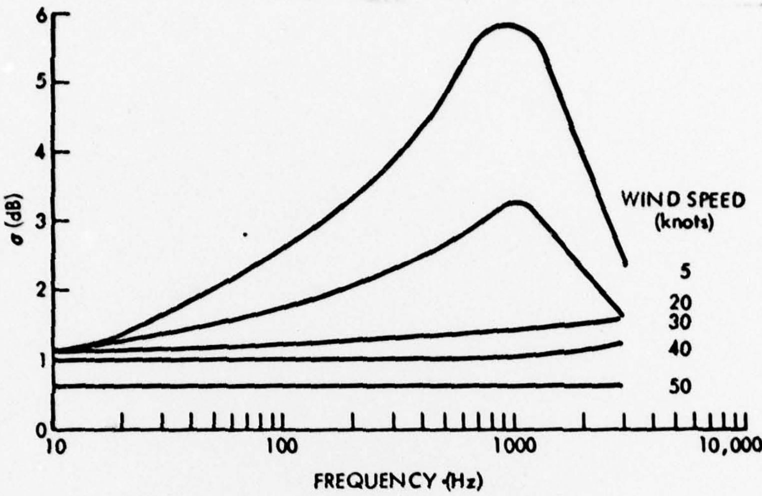
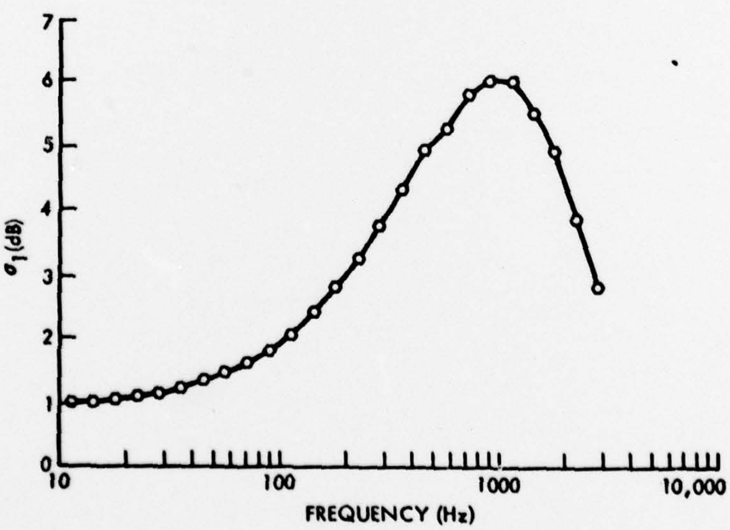


Fig. 4. Calculated spectrum levels of the non-wind-dependent and wind-dependent portions as derived from measured levels.

Fig. 5

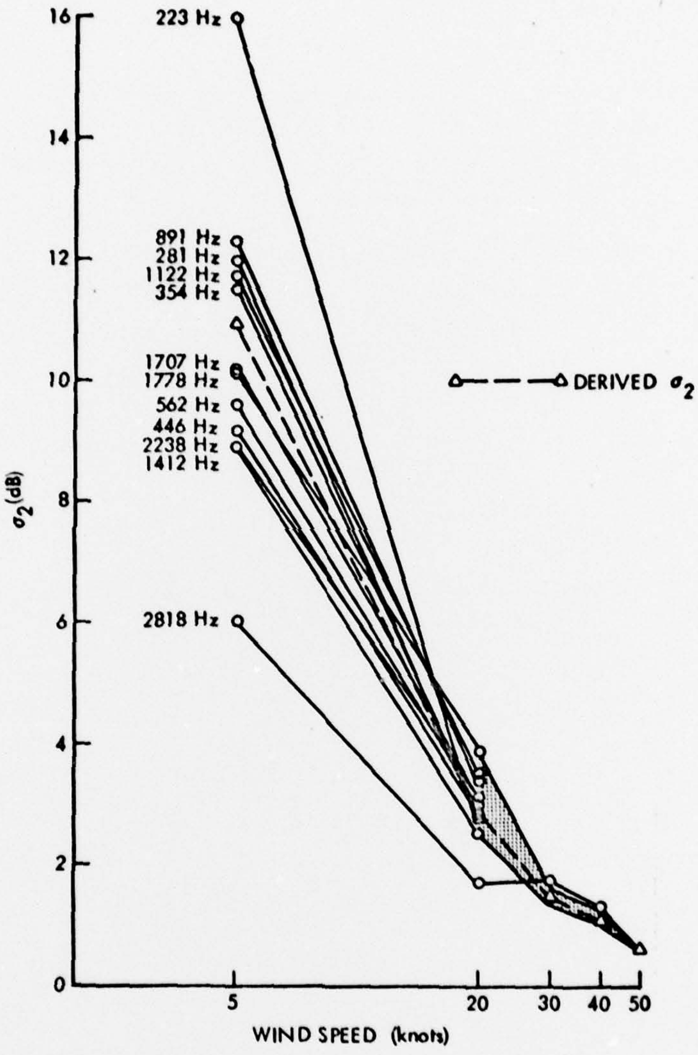


(a). The standard deviations of Perrone's measured spectrum levels.



(b). The best estimate of the standard deviations of the non-wind-dependent portions.

Fig. 5 (Cont'd)



(c). Standard deviations of the wind-dependent portions calculated from the measured values shown in Fig. 5(a) and the estimates shown in Fig. 5(b).

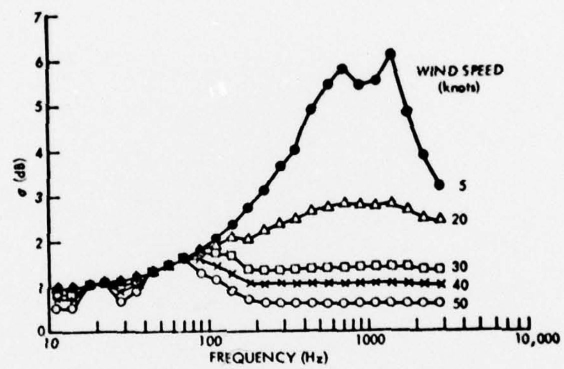


Fig. 6. The standard deviations resulting from a combination of the standard deviations shown in Figs. 5(b) and 5(c).